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OBSERVATIONS ON COMPRESSED AIR ILLNESS

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OBSERVATIONS ON COMPRESSED AIR ILLNESS.

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The opportunities afforded for the observation of the pathological effects of high atmospheric pressure have been relatively very few, and the testimony of every additional observer may be of value in aiding in the elucidation of a rather obscure subject. It is for this reason that I venture to publish these remarks, which embody my experience and the conclusions at which I have arrived as the result of that experience. It is not my purpose to discuss the physiological effects of compressed air on the human economy, for in my opinion observations along this line made during the progress of an engineering work of great magnitude would not afford trustworthy results, there being so many factors apart from the actual air pressure which would tend to render one's conclusions inexact. Neither is it possible within the limits of this paper to give an account of the history of the use of compressed air in engineering operations from the invention of the diving bell in the sixteenth century up to the present time. A very complete account of the subject has already been given by Dr. E. H. Snell in his excellent little book on "Compressed Air Illness," together with his own experience while acting as medical officer to the Blackwell Tunnel.

It seems probable that in the future compressed air will be used to a much greater extent than it has been in the past and the knowledge as to the best means of reducing to a minimum the suffering inseparable from this class of work will be of value not only to the workmen employed but also to the employers themselves. At the Baker Street and Waterloo Railway tunnel works, we had, considering the pressures employed and the length of the shifts, remarkably few cases of illness. The opinions which I hold as to the reason of this comparative immunity I will endeavor to express later.

It is a matter for regret that so much work under compressed air has been done in which no medical records have been kept, and this is not only the case with undertakings carried out many years ago, for even in so recent a work as the St. Clair Tunnel, under the St. Clair River in America, there seem to have been no accurate medical records, though I gather from a general description of the tunnel that there was much illness and that several deaths occurred. Among the best records of the last thirty years are those of Dr. Jaminet, of the St. Louis Bridge, and Dr. A. H. Smith, the medical officer at the construction of the Brooklyn Bridge. But while admitting the value of their observations I totally disagree with their conclusions as to the pathology of the condition and also as to some of the factors which are instrumental in its production.

For the better understanding of the conditions under which the men employed in the compressed air worked it will be well for me to give a short description of the tunnel. It was only in a certain portion of the tunnel that the use of compressed air was necessary—that part of it which ran through the ballast in the bed of the river Thames. The tunnel was reached by two shafts sunk through a staging erected in the river, the top of the tunnel being a few feet below the bed of the river. Before the shield had reached the ballast the river-crossing section of the tube was cut off from the other part by a brick diaphragm, into which a lock, with doors closing airtight, was fitted. At each end of the lock was a tap for the purpose of admitting the air from the pressure section when entering or for allowing it to escape into the other portion of the tunnel when leaving the compressed air. It was possible to fill the lock up to 30 pounds per square inch in one and a half minutes and to empty it at the same pressure in one and three-quarter minutes.

A few remarks regarding the astonishing rise in temperature when "locking-in" may be of interest. I have noted the mercury rise, when "locking-in" with a "full tap" at 30 pounds pressure, from 60° F. to 115°. During "locking-out" I have seen it fall from 90° to 46°. Foley assigned a very important place to this cold misty atmosphere in the production of the illness. While quite admitting that such sudden variations in temperature are not advantageous I do not consider that they play the smallest part in the etiology of the condition. The air was conducted from the air compressors to a large tank beneath the water, passing through this before being delivered into the tunnel, the idea being to cool it to some extent. I doubt whether this plan was very effectual, for on several occasions I took the temperature of the air as it left the supply pipe and found it to vary between 110° and 120°, according to the speed at which the air compressors were running. As it passed along the tunnel and escaped at the face it cooled to about 85°.

The pressures in the tunnel varied with the state of the tide and the nature of the ballast met with. As a general rule at low water the pressure was from 23 to 25 pounds per square inch, at high water from 28 to 30 pounds, and on several occasions it was as high as 35 pounds per square inch. It is to be remembered that these figures refer to pressures over and above the 15 pounds per square inch normal atmospheric pressure.

VENTILATION.

When it became necessary to use the air pressure the river-crossing tunnel had already progressed so that the face or shield end was 123 feet from the lock. Thus, to begin with, there was a fairly spacious chamber for the men to work in. The ventilation during the whole time that the shield was in the ballast was excellent, on account of the very free escape of air through the gravel at the face. I was in the habit of estimating three times daily the amount of air pumped into the tunnel, and found that it gave an average amount per hour of about 6,000 cubic feet for each man. This amount was well distributed, for, on my recommendation, the supply pipe emptied just at the lock, thus causing the air to sweep from one end of the tunnel to the other in order to escape at the

face. Before this was done the air at the face had shown 0.06 percent carbonic acid gas and at the lock end 0.09 percent. After the alteration in the pipe the whole tunnel showed the same amount, varying between 0.06 and 0.07, which degree of purity was maintained until Oct. 4th. On this latter date the shield being again in clay, the air could not escape at the face, and we had to depend upon artificial ventilation. The percentage of carbonic acid gas rose at once to 0.081, and then to 0.01, and could not be brought below 0.075 till Oct. 28th, when the compressed air was dispensed with. How this difference in purity affected the amount of illness I will point out further on. The tunnel was lighted by electricity which, by obviating the necessity for the use of candles or gas, materially improved the conditions. The men were divided into three gangs, each gang doing a "shift" of eight hours. The men working in the face, and who were exposed to wet, were provided with clothes which they changed on leaving the tunnel and which were dried before being again used. A well-warmed room was also provided for the use of the men to induce them to rest before going home, but of this they never took advantage. Hot coffee was supplied to them on leaving the tunnel and was much appreciated by them. I have no doubt that it was of benefit after the cold atmosphere of the lock. Smith states that it appeared to relieve to some extent the "nervous prostration which marked the return to the open air." I was never able to detect the smallest sign of nervous prostration in the men coming off a "shift," so I cannot offer any opinion as to the value of coffee in the condition. Before allowing any man to commence work in the compressed air I subjected him to a physical examination, paying particular attention to the condition of his heart and arterial system. Very stout men and those of advanced years were not accepted, though considerable latitude may be allowed in these conditions. Alcoholism, I consider, should debar a man from this class of work, and I rejected any man who on presenting himself showed signs of recent excess. Of the 120 men passed 88 had previously worked in compressed air, while 32 had no previous experience. The youngest man was 19 years of age and the oldest 52 years, the average age being just over 30 years.

In all, during a period extending from May 23rd to Oct. 28th, 1900, 47 cases of illness due to work in compressed air came under my treatment. These cases occurred in 40 different men, two having three attacks each and three two attacks each. In these figures I include only those cases which were of sufficient severity to call for treatment. I do not believe that a single man escaped a slight twinge of pain at some time or other to remind him of the nature of his occupation, but these were very evanescent and they cannot be dignified by the name of illness.

PATHOLOGICAL EFFECTS.

The pathological effects of compressed air are manifested at two distinct times and are due to entirely different conditions. The first class is purely mechanical, and is noted when going into, or when actually in, the pressure. The second class comprises those symptoms which are only seen after leaving the compressed air.

The symptoms consequent upon mechanical pressure per se consist of pains in the ears, frontal and maxillary sinuses, and in carious teeth. Pain in the ears is common when "locking-in" for

the first time especially if the pressure be rapidly admitted, but is rarely met with afterwards, unless there be a condition of "cold in the head," pharyngitis, etc., which interferes with the normal patency of the Eustachian tubes. The pain has all grades of severity, from a mere sense of oppression to the most acute agony. It is, of course due to the fact that the Eustachian tubes are blocked, the pressure outside the drum is greater than that in the middle ear and the membrane is pushed forcibly inwards. If the Eustachian tubes remain closed and the pressure be sufficiently great rupture of the tympanum may ensue. This actually occurred in two cases which came under my notice, in one of which I myself was the patient. The injury had no permanent ill effects in either case. Apart from actual rupture the relative vacuum in the middle ear brings about a congestive condition of its lining membrane, which, according to Dr. Snell, may result in inflammation which may be followed by suppuration. I had no case of this kind brought to my notice. The pains in the frontal and maxillary sinuses do not call for special mention. In my experience they were very infrequent, and I never observed them apart from a catarrhal condition of the nasal mucous membrane. In these cases, during "locking-out," there may be a discharge of blood-stained mucus from the nose. The foregoing conditions are, as before stated, dependent upon mechanical causes, and cannot well be considered as part and parcel of compressed air illness. Furthermore, in my experience, they never occurred apart from an abnormal condition of the mucous membrane of the nose or pharynx, therefore I cannot regard them as a necessary accompaniment of exposure to an atmospheric pressure above the normal.

In the second class are those symptoms which are only manifested after leaving the pressure. These symptoms, though perfectly distinct from each other, are, I believe, all due to the same underlying pathological condition. The most frequent and characteristic manifestation is pain, usually occurring in the joints, less frequently in the muscular structures of a limb. In only one of my cases were the muscles of the trunk affected. The pain may be confined to one joint or may be present in two or more joints, the latter condition being the more usual one. In my series of cases the knee was the only joint to be affected singly and this only occurred in four cases out of 47. The knee-joint is more frequently attacked than all the other joints combined, and in 19 of my cases the knees were the seat of pain apart from any other manifestation, and in 16 cases pain in the knees co-existed with other symptoms. Next in order of frequency came the elbow-joint which was affected in 11 cases, then the shoulder with seven cases to its credit. The hip-joint was the seat of pain in five cases, the wrist in three cases, and the ankle in one case. Any number of joints may be simultaneously affected. The pain varies from a mild ache to the most severe suffering, and in well marked cases I know of no condition which produces a greater degree of physical agony. The patient becomes pallid and perspires freely, the pulse is hard and rapid, and unless he is possessed of a considerable amount of self-control the man cries and groans. The pain has been described to me as "a feeling as if the joints were being twisted off," or "as if a dog were gnawing the bone." If untreated the pain may disappear in five or six hours or it may persist with diminished intensity for several days or even weeks. The onset of the pain may be at any time after coming

out of the compressed air. In some cases it comes on immediately, in others not for several hours. The longest interval in my own cases was five hours, but Dr. Snell gives notes of a case in which 14 hours elapsed between leaving the pressure and the appearance of the pain. As a rule not more than two hours elapse. I have almost invariably found that the sooner the symptoms appear after leaving the pressure the more severe they are. Swelling is not common in the joints, but is invariably present if the pain is situated in the muscles. I have never found any tenderness present, even vigorous friction relieving, rather than aggravating, the pain. I am aware that on this point my experience is directly contrary to that of most other observers. Epigastric pain and vomiting may occur and are usually very severe and refractory to ordinary treatment. In well-marked cases the pain is intense and the vomiting is persistent. This condition only occurred in about 10 percent of my cases and Dr. Snell only found it in a small percentage. On the other hand, Dr. Jaminet describes it in 78 percent of his cases, and Dr. Smith in 24 percent. Formication, or itching of the skin, followed by redness, may occur; only one such case came to my notice.

Cerebral symptoms.—Headache and giddiness are not uncommon as following exit from the compressed air. In four of my cases giddiness was very pronounced, the patients reeling and falling down. Pain in the head is not necessarily present, but may exist along with the giddiness. Vomiting is not uncommon in these cases, being cerebral in character and quite apart from any gastric disturbance. Visual troubles, such as diplopia and flashes of light, may be present. As a usual thing these symptoms are of short duration and they yield very quickly to appropriate treatment. Dr. Snell gives notes of nine cases of vertigo occurring after exit from compressed air. The onset in all the cases was sudden, and in six of them some amount of deafness was present, tinnitus occurring in four cases. In some of these cases the vertigo lasted for many months. No case of auditory vertigo, due to working in compressed air came under my notice, so I am unable to speak of it from personal experience.

Paralysis.—Paralysis only occurred in one of my cases, the condition being one of paraplegia with involvement of the bladder and rectum. Dr. Snell had only two cases at the Blackwall Tunnel, while in New York Dr. Smith observed it in 15 percent of his cases, and at St. Louis it was present in 61 percent. Dr. Smith says that the paralysis most often affects the lower half of the body but may include the trunk or arms. According to him pain may or may not be present in the limbs even when tactile sensation is lost. In my case the only pain felt was on each side of the spine in the lower lumbar region.

Death.—Death is not a very uncommon sequence of work in compressed air, and it may occur suddenly on leaving the pressure or after paralysis or other symptoms. Out of 76 cases of illness at St. Louis Bridge there were 12 deaths. Dr. Smith had three deaths in 110 cases, and four deaths occurred in sinking the caisson for the Londonderry new bridge and this with a pressure of only 28 pounds. As far as I can discover, the Forth Bridge and Blackwell Tunnel were the first works using high pressures which were put through without a fatality. At the Baker Street and Waterloo Railway Tunnel works we had no fatal cases.

DIAGNOSIS.

When we consider the devious workings of that peculiar statute known as the Employers' Liability Act it becomes a matter of some importance that these cases should be carefully diagnosed and differentiated from other conditions having somewhat similar symptoms. It must also be remembered that the pains may possibly be assumed, the man hoping thereby to be a financial gainer. I agree with Dr. Snell that the most important points in the diagnosis are the time and manner of the onset. Physical signs being rarely present in any form, there is little else to go upon. Personally I would not admit a case to be due to compressed air where twelve hours had elapsed from the time of leaving the pressure till the onset of the symptoms. Rheumatism, osteomyelitis, and arthritis deformans are not likely to be mistaken for the joint-pains of compressed air illness. The absence of any rise of temperature in the latter, together with its sudden onset and freedom from physical signs, will serve to distinguish it. I here insert a note on one of my cases which was interesting, not only from the point of view of diagnosis, but also because I am unable to find a similar case recorded in any of the writings on compressed air illness which I have been able to consult.

Case 1.—The patient, a strong healthy man, aged 50 years, rather inclined to be stout, had worked in compressed air before coming to the Baker Street and Waterloo Railway Tunnel works, and had been employed at these works for some time. On August 29th, 1900, he came out of the tunnel at 6 a.m. after doing an eight-hour shift. At about 6.30, when he reached home, he felt a pain "in the front of his chest." He at once got very short of breath and felt very distressed though the pain was very slight. He had a feeling of impending death. He managed to return to the stage, stopping every few yards to get his breath, and he reached there at 10.15 p.m. and I at once saw him. He was then in great distress and was unable to speak more than a few words at a time. His face was very dusky. I have never seen more severe dyspnoea. The pulse was 120 and very feeble and the respirations were 45. I at once auscultated his chest and found a most peculiar state of affairs. Posteriorly there was nothing abnormal and the supraclavicular regions were negative. But all over the front of the chest a most unusual sound was heard, audible throughout the whole respiratory cycle. I have never heard anything like it before, consequently I am unable to give any comparative description of it. It was very harsh and creaking, sometimes tearing, in character, and most marked between the third and seventh costal cartilages on the right side. I then percussed the chest with absolutely negative results, and on applying my stethoscope immediately afterwards I found that all the auscultatory phenomena had disappeared. There was no cardiac displacement and there were no murmurs, but the sounds were very distant and feeble. As the man was evidently in a serious condition I at once put him into the medical lock and re-compressed him up to 18 pounds, at which point all dyspnoea had gone and he felt perfectly well. This pressure was allowed to "leak out," in 70 minutes and the patient came out of the lock feeling quite well. There was no return of the symptoms. No physical signs could be discovered after coming out.

Now in this case there might have been considerable difficulty in

the matter of diagnosis. The mode of onset certainly pointed to compressed air as the causative factor, but it was hardly possible to be certain until the immediate cure of the condition by re-compression removed all doubt as to the nature of the trouble.

ETIOLOGY.

The one essential for the production of this illness is, of course, a sojourn in an atmospheric pressure above normal. This, however, does not in itself cause any of the symptoms given above but only brings about the conditions necessary for their development after the subject returns into a lower pressure. It must be thoroughly understood that there are no manifestations of this illness so long as one remains in the compressed atmosphere; it is my opinion that a man might live in a pressure of three atmospheres for an indefinite time without necessarily experiencing any ill effects. In addition to the essential cause there are other factors which are very important, the first two in order of importance being the length of stay in the pressure and the amount of carbonic acid gas present in the condensed atmosphere. The influence which the latter has upon the former of these two factors is so great that it is hard to separate them in considering the share which each one has in the production of the illness. Dr. Snell has enunciated a law that the amount of illness varies inversely with the amount of fresh air supplied. With this I thoroughly agree, and when considering the length of time spent in the pressure the carbonic acid gas factor must be thought of, and, within certain limits, it may be laid down that the time which may be spent in the pressure without resulting bad effects depends very largely upon the amount of carbonic acid gas present.

Leaving aside the question of ventilation for the moment and assuming the percentage of carbonic acid gas to be a fixed quantity, then the length of stay in the pressure is, in my opinion, the most important accessory in the etiology of the disease—far more important than the time employed in leaving that pressure. At the Baker Street and Waterloo Railway Tunnel there was no case of illness occurring in a man who had not been at least three consecutive hours in the pressure. In addition to the regular eight-hour workers there were many men, such as fitters, plate-layers, gangers, etc., who spent variable periods of time in the condensed atmosphere, so that I had an excellent opportunity of proving this point.

Regarding the relative importance of the length of stay in the pressure as a factor in the production of the disease, opinions have differed. Dr. Jaminet recommended short shifts at the St. Louis Bridge, but, nevertheless, he considered the time spent in the "locking-out" as of primary importance. According to Dr. Snell, Mr. Eads, the chief engineer of the bridge, was the first to call attention to the fact that the length of stay was more concerned in the production of illness than the rapidity of "locking-out." Dr. Smith attached great importance to the length of stay in the pressure and he formulated the law that the danger is as the degree of pressure to which the person has been exposed multiplied by the duration of the exposure. At the Brooklyn Bridge the pressure rose gradually, with the depth of the caisson, from 18 pounds to 36 pounds per square inch, the length of the shifts being four hours at first, gradually reduced to two hours as the pressure increased. Even with these short shifts, Dr. Smith reports 110 cases of

compressed air illness as occurring in four months. At the Baker Street and Waterloo Railway Tunnel where eight-hour shifts were worked, there were only 47 cases in five months. At first sight these figures would appear to show that the length of stay does not play a role of any importance in the production of the illness. But it is precisely here that the carbonic acid gas factor comes in and proves itself to be of such importance. At the Brooklyn Bridge caisson the air contained 0.33 percent of carbonic acid gas, while at the Baker Street and Waterloo Railway Tunnel, as has already been stated, the percentage up to the last three weeks was kept at from 0.06 to 0.07. Dr. Smith seems not to have considered ventilation as of any importance, and he makes the remark that "this amount (0.33) of vitiation was found not to affect the men unfavorably." In my opinion it was just that vitiation which was responsible for his large number of cases. No doubt it had also much to do with the "nervous prostration" which he observed in men coming out of the pressure. It is true that Dr. Smith had a larger number of men than were employed at the Baker Street and Waterloo Railway Tunnel, but had we worked in four-hour and two-hour "shifts," instead of in "shifts," of eight hours, the number of our cases, would, in my opinion, have been insignificant.

Dr. Snell claims to have been the first to point out the relationship between the amount of illness and the fresh air supplied to the compressed air space, and he gives some very interesting tables from his experience at Blackwall in support of his views. My own observations on this point were necessarily limited as the air-supply was large and constant up to nearly the end, but the figures I am able to give are, I think, sufficiently striking. From May 23rd to Oct. 4th, with an average of 6,000 cubic feet to each man per hour, there were 34 cases, say eight cases per month. Following this, with an average of 1,700 cubic feet to each man, per hour, there were 13 cases in a period of 12 days. I found also that the cases occurring during the latter period came on sooner after leaving the pressure, and were of greater severity than those occurring during the time of good ventilation.

I do not assign a very important position to rapid "locking-out," as a cause of the illness, though I am firmly of the opinion that could this process be sufficiently prolonged it would probably altogether prevent subsequent symptoms. But in order to achieve this result three-quarters of an hour at least would be required to be spent in coming out of a pressure of 30 pounds to the square inch, and this, from an economic point of view, would be impracticable. Some observers have laid down very precise mathematical rules as to the length of time to be spent in reducing given pressures, though it is difficult to see on what these rules are based. Dr. Smith says that five minutes should be allowed for each additional atmosphere, while Dr. Jaminet gives one minute for each additional six pounds of pressure. At the Baker Street and Waterloo Railway Tunnel it was possible to "lock-out" of 30 pounds pressure in one and three-quarter minutes during the first three months. After that the exit tap was altered so that to leave the same pressure required at least six and a half minutes. This alteration did not in the slightest degree affect either the number or the severity of the cases.

There are some minor predisposing causes which have been assigned different degrees of importance by various authorities. Among these newness to the work, age, alcohol and obesity are

the chief. With regard to an old hand being less liable to compressed air illness than a newcomer opinions differ. Dr. Smith strongly adheres to this view, though admitting that some very severe cases occurred among old hands. Dr. Snell does not admit the increased liability of a new hand to the disease, but says that it is very difficult either to prove or disprove it. Personally, it is a point upon which I am uncertain, though my figures would tend to show that a man is more susceptible when he first begins this class of work than after having been engaged in it for a greater or less period. Of 88 men who had previously worked in compressed air 25 were affected, or 28.4 percent; while of 32 men who had no previous experience of such work 15 were affected, or 46.8 percent. Of the 40 men who were affected, in 16 the illness occurred after the first "shift"—that is to say, in 40 percent.

Age has been considered to be an important factor, the amount of illness varying in proportion to the age. The only statistics which I can find are those given by Dr. Snell from his own experience, and covering, as they do, a large number of men of all ages, they have an especial value. He concludes that below the age of 20 years men are singularly exempt from this illness; between the ages of 25 years and 45 years the liability to illness does not vary to any great extent, but is about twice as great as between the ages of 20 years and 25 years, and that after the age of 45 years the liability increases very considerably. My own conclusions, though based upon a much smaller number of men, agree with those of Dr. Snell, and I am of the opinion that young men stand compressed air better than do those of more advanced years. But it is only in the very young ones that a marked immunity is observed, the amount of illness from 25 years to 40 years not varying much according to the age.

Fulness of habit has been noted by many observers as specially predisposing to the untoward effects of compressed air. Dr. Smith made a strong point of this in his essay on caisson disease, and he gives figures in support of his views which show that of 86 cases of illness the spare men were responsible for 28, the medium for 22, and the heavy for 36. He adds, "Considering that among laborers below the age of 45 (and none were above that age) the class described as heavy are very much in the minority these figures are sufficiently striking." As I excluded all men who were conspicuously stout I have not been able to form any opinion from observation on this point. But I am quite certain that the cases occurring in moderately large men were neither more numerous nor more severe than those in men of light build.

Alcoholism has been said to strongly predispose to compressed air illness, a man who has been drinking heavily being frequently a sufferer, and certainly some of my most severe cases occurred after a too free indulgence. But this is a point upon which it is hard to come to a satisfactory conclusion, for the reason that, with two exceptions, all the men used alcohol, the majority freely, so that no comparative statistics could be obtained. But I am inclined to the view that alcohol is a predisposing factor of considerable importance.

Muscular exertion following upon exit is insisted on by Dr. Jaminet as being of importance in bringing about the symptoms, and he noted a diminution in his cases when the men were drawn up instead of reaching the top of the caisson by climbing ladders.

Dr. Smith also supports this view, but admits that he has no figures to offer. At the Baker Street and Waterloo Railway Tunnel the men were drawn up in a cage and were forbidden to mount the ladders, but always hurried away as soon as they reached the top. Two of the men used bicycles, riding home a distance of six miles immediately after coming out of the compressed air, neither of them having an attack throughout the whole five months. I have never been able to see any reason for supposing that muscular exertion after exit increases the liability to the illness though I do not deny the possibility of its being so.

PATHOLOGICAL THEORIES.

Very many theories have been put forward in an endeavor to explain the manner in which compressed air causes the symptoms for which it is responsible. But possibly even more surprising than their number is the fact that so many of these elaborate theories do not in any way harmonize with the observed symptoms and conditions. In many cases it appears as though, so long as the theory happened to be vague and abstruse, its sponsor was perfectly indifferent as to whether or not it could be reconciled to the facts. The symptoms have been variously ascribed to exhaustion, hemorrhage, rheumatism, congestion of various parts, carbonic acid gas poisoning, and supersaturation of the blood by the compressed atmosphere. It would be quite impossible within the limits of this paper to give, with any sort of completeness, the arguments put forward by those who happen to pin their faith to one or other theory. All that can be done is to examine them in a general way and to attempt to point out where, in my opinion, they appear to fall short.

The exhaustion theory is based on the hypothesis that an increased metabolism follows a stay in compressed air owing to the greater amount of oxygen present. This is purely hypothesis, for, Dr. Snell points out, no experiments have as yet proved that any such increased activity of the vital processes does occur. On the contrary, many observers have arrived at the conclusion that there are no grounds for such a belief. Personally, though my observations were clinical, and not experimental, I have not been able to find any reason for holding that work in compressed air is associated with increased metabolism. Appetite has been said by many to be increased and Dr. Smith says in regard to this that it "seems to point to an increased waste of tissue to be supplied by a greater consumption of food," though he would not accept the explanation as conclusive, believing that this could not occur without increased temperature. I do not presume to doubt those who say that appetite is generally increased, but in my own experience I have not found such to be the case. I carefully questioned some 30 of the more intelligent of the men regarding their appetites when working in compressed air. Only two said that they ate more, the majority that they noticed no alteration, while a few stated that they did not use as much food. Neither is there any rise in temperature. But let us admit, for the sake of argument, that this increased tissue metamorphosis does occur, can we account for the symptoms in this way? Dr. Jaminet held an affirmative opinion, and in fact his treatment consisted altogether of stimulants and nourishment, but by what process of reasoning he arrived at this conclusion it is

beyond my power to conjecture. My own opinion so thoroughly agrees with that of Dr. Snell that I cannot do better than quote his own words: "... But if severe and often excruciating pain in the limbs, and elsewhere, paralysis of the legs, bladder, and rectum, and sudden death, are each and all to be ascribed to 'exhaustion,' this term must surely be employed in some more special and technical sense than is usual." Furthermore, this theory offers no explanation of the fact that the illness depends largely on the amount of carbonic acid gas present—i.e., the less oxygen the more illness. Neither does it account for the curative action of recompression in these cases nor for the complete absence of symptoms so long as one remains in the compressed air.

The theory that carbonic acid gas causes the illness by direct poisoning requires no more refutation than the statement that the symptoms of poisoning by this gas bear no resemblance to those met with in compressed air illness.

Congestion of the brain, spinal cord, and other organs is considered by Dr. Smith in his essay on caisson disease, by Dr. Moxon in the Croonian Lectures in 1881, and by many other observers to be the cause of this illness. Dr. Smith says that "it is probable that the pathology of this disease is not entirely uniform in all cases," but does not doubt that congestion is the chief element in it. But in his further elaboration of this theory he assigns congestion the chief and only place, although not bringing forward a single fact which goes to prove his contention. He begins by making the statement that the centres will be congested at the expense of the periphery in a compressed atmosphere, and having laid down this law in no uncertain manner, deduces a second law, "that firm and compact structures will be congested at the expense of those more yielding," and on top of this a third law, "that structures within closed bony cavities are congested at the expense of all others." Now it is the easiest thing in the world to deduce a law from a statement, the difficult matter being to be quite certain that the statement is correct. Does the blood, as Dr. Smith says it does, pass from a place where the pressure is greater to one where it is less, and if so where does it go to find a place which is not already filled with matter, either fluid or solid, or how can it increase the tension in these central parts when, as Dr. Snell well puts it, "blood-pressure is everywhere raised and every one part of the body presses with greater force on every other part"? The only compressible parts are the free gases in the alimentary canal, and I can corroborate Dr. Snell's opinion that this potential space is principally occupied by the abdominal wall being pressed in, as, from my own observations, the latter is the case when one goes into a compressed atmosphere. If the blood under pressure leaves, say, the periphery of a limb, how does it do so except as a result of compression of that limb? Dr. Smith says the solid structures resist compression. How, then, are the fluids contained in the solid structures going to be driven out of them? It would seem as reasonable to say that one might by compressing a glass bottle squeeze water out of it without altering its shape. In order for the pressure to act upon the blood it must necessarily do so by compressing surrounding structures. But in compressed air there is not the least evidence of this taking place. The limbs are not altered in the least degree either in size or shape. Dr. Smith says that superficial veins are obliterated and that the skin is anaemic, and he even makes the statement that the hands

are shrunken and shrivelled owing to the blood being squeezed out of them. Now I have repeatedly examined men while in the pressure in order to ascertain to what extent I could corroborate these observations of Dr. Smith's. In my experience I can emphatically say that these phenomena did not occur. The skin does not become anaemic, the veins are not effaced, nor are the hands altered in appearance in the slightest degree. But on other grounds it is difficult to admit the engorgement of the internal structures assumed to occur by the exponents of this theory. Is it reasonable to suppose that a man could work, and work hard, for eight consecutive hours with his brain, spinal cord, liver, etc., in such a congested state, and could do his work without the slightest feeling of discomfort, and keep it up, on and off, for years without discoverable ill effects? To my mind it is most unreasonable. Again, how does this theory agree with the actual symptoms of the illness? Dr. Smith holds that the vessels both in the congested and anaemic parts will suffer from a loss of tone which will bring about a lowering of tension in the vascular system. He also appears to believe that while in some cases the pains are of local origin in most cases they are spinal. I believe all the joint and muscular pains to be local and not spinal in origin. And in any case will the fact that the vessels are suffering from loss of tone be sufficient to give rise to a pain of such intensity? Can the case of cardiac dyspnoea to which I have referred be put down to congestion, spinal or otherwise. Although Dr. Smith did not use recompression as a therapeutic measure he was impressed with the fact that when a man returned into the pressure the symptoms vanished. He says that he would expect re-compression to be of special value in "paralysis not dependent on extravasation of blood." But if paralysis is common with other symptoms were dependent on congestion how would re-compression be of service? It would simply bring about congestion of the cord once more. Dr. Smith does not attempt to explain why he thinks re-compression would act beneficially, and if one were held to the congestion theory it could not be satisfactorily explained.

In the *New York Medical Record*, 1890, Dr. Corning attributes the symptoms to anaemia of the cord. But it is only in exceptional cases that there are any symptoms which can properly be referred to the cord, and it is perfectly justifiable to suppose that the same cause is at the bottom of all the symptoms, depending altogether for its effect on the part of the body upon which it acts. Finally, neither of these theories explain why carbonic acid gas should be a factor in the production of the illness only second in importance to the pressure itself.

Supersaturation of the blood.—Now we come to the theory which has for its foundation the law of Dalton, which enunciates that fluids absorb gases in direct proportion to the pressure. Water dissolves at 10° C. and under one atmosphere pressure oxygen 0.028 part, nitrogen 0.014 part, carbonic acid gas 0.90 part. It is held that during a sojourn in compressed air the blood becomes charged with the atmospheric gases proportionately to the pressure and that after exit, the pressure being removed the blood is no longer able to hold the air in solution and it may become free in the vessels and surrounding tissues and thus give rise to the various symptoms met with. We have in this argument an adequate explanation of the symptoms not only of joint pains but of paralysis and other manifestations. I am of the opinion that the case of cardiac dyspnoea

which I have recounted can be explained very reasonably as being due to extravasation of air into some situation where it caused pressure on, and consequent embarrassment of, the heart, though what that exact situation was I confess that I am not able to say. Now regarding the absorption by the blood of gases under pressure it has been shown by Bert that such absorption does take place although not exactly according to the rule laid down in the law of Dalton. Hoppe found that in animals killed by a rarefied atmosphere there were bubbles of free air in the blood. He concludes that the same effect takes place in passing from a condensed to a normal atmosphere. Bucquoy considered that in a compressed atmosphere the amount of gases absorbed by the blood increased in accordance with physical laws and that on decompression gas must escape and may cause in some cases joint and muscular pains and hemorrhages. Dr. Snell as a result of his observations strongly supports this theory of supersaturation of the blood. Now what arguments are there against the tenability of this theory? I have carefully observed every case of compressed air illness which came under my treatment and have considered the conditions which appear to bring about an increase or decrease in the number of cases, and I have been unable to find any fact which cannot be reasonably explained if we accept supersaturation of the blood as the underlying cause of the symptoms. Dr. Smith, it is true, objects to this theory on the very insufficient grounds that frequently the symptoms do not appear until several hours after leaving the pressure, whereas, in his opinion, if the symptoms were produced by free bubbles of air in the blood-vessels this condition should be at its maximum at once after leaving the pressure and should give rise to the symptoms immediately. His second objection is that the fact of the "comparative immunity from danger which results from repeated exposures to compressed air" could not be explained if the action were due to purely physical causes. He says: "The obstruction of the vessels described by Bert is a condition of which the system could never become tolerant by frequency of repetition." The first objection may be answered by pointing out that the disengagement of the air from the blood is not an instantaneous process, and that very many of the fine bubbles may have to collect before even a capillary vessel can be blocked, and, as Dr. Snell further points out, a still greater collection must take place before stretching and rupture of the capillaries can ensue. Regarding Dr. Smith's second objection it may be said that the comparative immunity acquired as a result of repeated exposures to compressed air is as yet not proven, though personally I am inclined to the opinion that some degree of immunity may result. But even if this be admitted I can see no reason why the vascular system should not adapt itself to this condition equally as well as to the condition of congestion described by Dr. Smith. Probably in many of the cases the vessels do not rupture, but the air passes through them into the surrounding tissues. Why should not the vessels acquire a resistance to this or to rupture as well as to congestion? This theory is capable of explaining why the length of time spent in a condensed atmosphere should be of such moment, for saturation of the blood will only take place more or less gradually. We can also see why higher pressures are more dangerous than lower ones if we admit the operation of Dalton's law in these cases. It also explains why the symptoms are never observed so long as one remains in the pressure, but only

after exit. Furthermore, I am satisfied in my own mind that this theory affords a reasonable and scientific explanation as to why an increase in the carbonic acid gas should bring about an increase in the amount of illness, and also why, with an atmosphere containing 0.06 percent carbonic acid gas at the Baker Street and Waterloo Railway Tunnel, we had no cases occurring under a three hours sojourn in the pressure. When we consider the relative solubility of oxygen, nitrogen, and carbonic acid gas, it is within the bounds of probability that the latter is the one dissolved in greatest amount in the blood, though present in such a small quantity in comparison with the other component gases of the atmosphere. The application of the law of Dalton explains why pressure, length of stay in that pressure, and amount of carbonic acid gas present should be so intimately connected one with another that it is impossible to consider one without the others. It is true that Bert in analysing the bubbles of air obtained in his experiments upon animals found them to consist chiefly of nitrogen. But as Demarquay, quoted by Dr. Snell, has shown, free gases existing in the tissues of the body are absorbed at different rates, and while carbonic acid gas is absorbed in 45 minutes nitrogen may be discovered after several weeks. Is it not possible that the length of time intervening between death and necropsy in Bert's experiments may have been sufficient for the disappearance of the carbonic acid gas? This theory also enables us to comprehend why rapid re-compression followed by a long "locking-out," are in a large majority of cases curative in all forms of the illness, the air being re-absorbed and the gradual "locking-out" enabling it to escape through the lungs. It also accounts for the fact that the sooner re-compression is practised after the onset of the symptoms the more satisfactory are its results.

MORBID ANATOMY.

There having been no fatal cases at the Baker Street and Waterloo Railway Tunnel works, I have had no opportunity of seeing for myself the post-mortem conditions present. There have been a fair number of necropsies following death resulting from compressed air, but many of them seem to have been incompletely performed. Congestion of various organs has usually been present and in some cases there has been effusion beneath the arachnoid and blood-clots under the dura mater of the cord. Dr. Smith details one of his cases, in which Dr. Janeway, of New York, performed the necropsy. Death had taken place suddenly within two hours of exit. Nothing abnormal was found except congestion of the lungs. It is not stated whether the cavities of the heart were examined for free air bubbles. The spinal canal was not opened. So far the post-mortem examinations made in this condition are not absolutely reliable, for they seem to have been conducted, as far as can be made out, without the precautions necessary for the discovery of free air in the tissues and vessels. The experiments of Bert on animals seem to have been followed by much closer post-mortem investigations.

REMOTE EFFECTS OF WORK IN COMPRESSED AIR.

Does the human organism suffer any ill effects which may be described as chronic as a result of being subjected to the action of

compressed air? I can only say that I have never been able to discover anything which would lead me to answer this question in the affirmative. Many of the men who came before me had worked on and off in compressed air for periods of five, six and seven years, yet I was unable to find any pathological condition in their organs or arterial systems except in one case—viz., that of a man, 42 years of age, who had worked for varying periods during the last seven years in compressed air and who showed marked arterio-sclerosis apart from any cardiac or renal condition which could be discovered. This sclerosis may have been caused by his occupation, but it is impossible to say definitely that it was.

Regarding the paleness of the face and the general unhealthy appearance of compressed air workers insisted upon by Dr. Smith, I may say that I was not able to detect any greater degree of pallor in these men than was present in men working in other parts of the tunnel, where compressed air was not used, and which is found in most men working underground. Dr. Snell says in this connection that at the Blackwall Tunnel as ventilation improved the pallor became less marked, so that eventually he could not pick out an air-pressure man by his complexion though previously he had been able to do so.

TREATMENT.

In the great majority of cases only one treatment is necessary and that is re-compression. For this purpose we had a medical air-lock erected on the stage, consisting of a boiler placed horizontally. At one end was a door which was air-tight when closed, and the interior was fitted with bunks, lighted by electricity and heated by steam. A small window and speaking tubes completed the arrangement. It was connected with the air-compressors and was fitted with a pressure gauge and the necessary taps. The sooner re-compression is practised after the symptoms appear the better as a rule are the results. If a long period has elapsed, even though the pain may be benefited, there is always in joint cases marked stiffness remaining, the condition then being not an acute one but simply the result of the bruising and stretching undergone by the tissues.

The amount of pressure needed for relief depends more on the severity of the case than on the original pressure which produced the symptoms. Persons attacked after coming out of 30 pounds per square inch pressure may feel perfectly relieved when the pressure in the medical lock amounts to 18 pounds, others may require to be re-compressed up to 25 pounds, although the pressure they came out of was only 23 or 24 pounds per square inch.

Decompression must be slow, and I think it is of advantage not to reduce the pressure faster than at the rate of one pound in three minutes. In my experience re-compression never fails to stop the pain but there are exceptional cases where it returns shortly after exit. In some of these a second re-compression is effectual, in others it is quite useless, and I have given an example of each class in the appended illustrative cases. If the pain returns it invariably does so in the original situation, and the fact that pain should ever return after re-compression is probably owing to the creation by the first attack of a *locus minoris resistentiae* which renders the passage of air into the tissues easier than escape by way of the respiratory system. In the cases in which the pain returned I had recourse to

morphine given hypodermically. It must be used in fairly large doses, a quarter of a grain not being sufficient to control the pain in any of the three cases in which I used it.

Ergot is highly spoken of by Dr. Smith who considered it superior to morphine in relieving the pain. I never found it to be of any benefit except in one variety of case—that in which giddiness and headache are the symptoms. I have used it in doses of from one to two drachms of the fluid extract in cases of this kind and always with the greatest benefit.

In the acute cases it is my experience that liniments are practically useless and the same is true of bandaging.

In the cases of stiffness following the acute symptoms I have used the liniment containing aconite and belladonna recommended by Dr. Snell with the greatest benefit.

ILLUSTRATIVE CASES.

Case 2.—The patient was a strong and healthy man, aged 28 years, who had been working in the Baker Street and Waterloo Railway Tunnel for six days. He had finished an eight-hour "shift" at 6 a.m. on May 29th, and three hours later he had very severe pain in his left hip and thigh. He returned to the works at 8.15 p.m., when I saw him. The pain was then very severe, the left thigh being much swollen, and he could only walk with much difficulty. He was put into the medical lock and the pressure raised to 18 pounds, at which point the pain had practically gone. The pressure was reduced to normal in 45 minutes and he came out feeling quite well, but with much stiffness in the limb. There was still considerable swelling, so the thigh was firmly bandaged and he was given a liniment. When seen on the night of May 30 he stated that he felt quite well and that there was no return of the pain.

Case 3.—The patient in this case was a man, aged 40 years, who had had previous experience in compressed air. He was a strong healthy man. He came out of the pressure at 6 a.m. on June 14th, after the regular eight-hour "shift," the pressure then being 28 pounds. At about 8.30 a.m. he was seized with pains in his left knee and in his right shoulder and elbow. He returned to the stage at 2.30 p.m. and I re-compressed him up to 25 pounds, the "locking-out" occupying 50 minutes. The pains before going into the lock were most intense, but on coming out the shoulder and elbow were perfectly well, the knee being slightly stiff. There was no return and he went on his "shift" at 10 p.m.

Case 4.—The patient was a man aged 23 years, had worked in compressed air at Glasgow, and had been at the Baker Street and Waterloo Railway Tunnel works for over a month. He had never been affected before. He came off his "shift" at 6 a.m. and immediately on leaving the lock he was seized with most acute pain in his left arm between the shoulder and elbow. He went back into the pressure and obtained instant relief, but on coming out again the pain returned as severely as before. I was sent for at 9.15 when I found him in great pain. The left upper arm was much swollen and on palpitation it gave a crepitan sensation to the examining fingers. He was put in the medical lock and re-compressed up to 22 pounds, coming out in 50 minutes. The pain returned but not so severely as at first. I then rubbed his arm with a liniment containing aconite and belladonna and applied a moderately tight bandage

without the slightest relief. He was therefore again re-compressed up to 12 pounds, at which point the pain had gone. The "locking-out" took 30 minutes. There was no return of the pain after this second re-compression. The crepitant sensation imparted to the fingers in examining the arm in this case would lead one to suppose that it may possibly have been due to free air in the tissues. Dr. Snell had a similar case occurring in the thigh.

Case 5.—The patient was a healthy man of small build, aged 26 years, who had had no previous experience in compressed air. He "came off" at 6 a.m. on Oct. 12th, after doing his first "shift," and within ten minutes he experienced most intense pain in both knees. He returned at once to the stage and I saw him a few minutes later, and he was then crying and groaning and apparently suffering very greatly. There was no swelling of the joints themselves, but there was a considerable amount of swelling in the muscles of the thighs. He was put into the medical lock and was re-compressed up to 22 pounds, at which pressure the pain completely went. The pressure was reduced to normal in one and a half hours, and the pain at once returned. He was then given one and a half drachms of the fluid extract of ergot and was re-compressed to 22 pounds, two hours being occupied in "locking-out." The pain immediately returned and was so intense that I injected a quarter of a grain of sulphate of morphia hypodermically and had to repeat it in half an hour. This controlled the pain and the patient slept till 7 p.m., going home soon afterwards free from pain but hardly able to walk on account of the stiffness of his knee joints.

Case 6.—In this case a strong, healthy, spare man, aged 43 years, who had had no previous experience in compressed air, came out of the pressure at 6 p.m. on Oct. 10th, after being in for four hours, and about an hour later he was seized with most severe pain in the abdomen, the knees, the shoulder and the elbow. The abdominal pains were most excruciating and were accompanied by severe and intractable vomiting. He had two physicians at his own home, who on failing to relieve him advised him to come back to the works. He was brought back in a cab about 4.30 a.m. on Oct. 11th, and I saw him about 15 minutes later. He was in great agony, groaning and writhing with pain, and had to be lifted into the medical lock. During re-compression the abdominal pain increased and was so intense that he rolled on the floor of the lock but when the gauge showed 24 pounds pressure the pain almost completely left him. The pressure was reduced to normal in 80 minutes, and when he came out of the lock he was quite free from abdominal pains and the only joint which was still somewhat painful was the left shoulder. In a short time he was able to proceed home. When seen on Oct. 12th the patient said that he felt quite well except for stiffness in the left shoulder. He was advised not to resume work in the air pressure.

Case 7.—This patient came out of the pressure at 7 p.m. on August 20th, having been in just over three hours, the pressure being about 28 pounds. Almost immediately he was seized with the most intense pain in "the small of the back on each side of the spine." It rendered him helpless and made him feel sick. I saw him at 7.15 p.m. and he was re-compressed, the pain having vanished by the time a pressure of 15 pounds was reached. Decompression occupied 65 minutes and he was perfectly well on leaving the lock. When seen on the morning of the next day he stated that he felt perfectly well. There was no return of the pain.

Case 8.—The patient was a strong healthy man, aged 23 years. He had had previous experience in compressed air and had worked at the Baker Street and Waterloo Railway Tunnel works from the commencement. He came out of the pressure at 6 a.m. on Oct. 16th after working for eight hours, and an hour later he felt very giddy and began to vomit very violently. There was no pain in the head or elsewhere. He was quite unable to stand. This condition continued for two days and on the third day he began to improve. On Oct. 22 he returned to the works and I saw him for the first time. He was still somewhat giddy, so I gave him one and a half drachms of the fluid extract of ergot and in an hour he said that his head was quite clear. At no time was there any loss of power anywhere, the helplessness being due altogether to giddiness. The vomiting was severe and intractable.

Case 9.—The patient, who was a healthy, spare man, aged 45 years, had been working in compressed air on and off for the last six years. He had never been affected by it in any way. He had been working at these works since the commencement of operations without having had any trouble. He came out of the pressure at 10 p.m. on Oct. 13th, and 15 minutes later he had very severe pain in the lower lumbar region on the right side of the spine and pain of a less marked character on the left side. He also had abdominal pains of moderate intensity. He returned at once to the stage, his lower limbs by this time being completely useless and sensation being much impaired as high up as the iliac crests. I was not sent for, some of his fellow-workmen taking it upon themselves to re-compress him, and at a pressure of 18 pounds all trouble had disappeared and he could use his lower limbs as well as ever. But they reduced the pressure to normal in less than ten minutes, and, as was to be expected, the pains in the back and the paresis of the lower limbs returned just as he reached home. On Oct. 14th the lumber pain had disappeared, but power in his legs was still absent and he had also lost power over his bladder and rectum, a catheter and enemas being necessary. He was brought to the stage on Oct. 15th and I saw him when I obtained the information which I have given above. He was then quite unable to move his right leg and could only just move the left leg. Sensation was impaired, but not completely gone, as high as the iliac crests in front and behind. I had little hope of re-compression or of ergot being of use, the interval having been so long, but I thought it well to try them. He was given one drachm of ergot and was re-compressed up to 25 pounds, the pressure being reduced to normal in an hour and three-quarters. There was no improvement at the time but an hour later he was able to lift both legs and he said that he did not feel so helpless. Having given him instructions regarding himself he was taken home shortly afterwards. He improved daily and within a week was able to move about on his legs, but the use of a catheter was still necessary. I last saw him on Nov. 9th. He could then walk fairly well, and sensation was much improved, but it was not yet normal and a catheter was still necessary. In this case I believe recovery will be complete, though it may be several months before the man is able to engage in his ordinary work. As a rule, in these cases, the bladder is the last to recover, and the use of a catheter may be necessary for a considerable time after the limbs have completely recovered.

The pathology of these cases of paraplegia in which there is

recovery can reasonably be explained by the pressure of air bubbles either in or outside the vessels upon the nervous centres in the cord. It is not probable that where recovery takes place there has been rupture of the vessels and consequent hemorrhage, though in those cases where there is no recovery but in which the patient remains paraplegic it would appear that this is what happens. In the foregoing case the pressure on the cord was certainly not due to hemorrhage because the man was at once completely cured by re-compression, and had the "locking-out" occupied an hour instead of less than ten minutes I am perfectly satisfied that there would have been no return of the paraplegia. When I saw the man nearly 48 hours had elapsed, and he was probably then suffering not so much from the pressure as from the results of that pressure on the nervous structures of the cord, but from the fact that the second re-compression was of some benefit there was probably some free air even at that time.

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